International Journal of Engineering Research and Science & Technology

www.ijerst.org

ISSN : 2319-5991

Vol. 22 No. 2(1) (2026)

ijerst.editor@gmail.com

editor@ijerst.com

Intelligent ESP32-Based IoT Waste Management System for Efficient Waste Collection Solutions

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Abstract

The rapid growth of urban populations and waste generation has created significant challenges in waste management, with global municipal solid waste expected to exceed 3.4 billion tons annually by 2050 and inefficient collection systems increasing operational costs by nearly 20–30%, while smart waste management technologies are projected to grow at over 18% annually. Additionally, improper waste handling leads to environmental pollution, health hazards, and unhygienic urban conditions, emphasizing the need for intelligent monitoring systems. Traditional waste management systems rely on fixed collection schedules and manual inspection, which often result in overflowing bins, unnecessary fuel consumption, and increased labor costs. Furthermore, conventional systems lack real-time monitoring, waste classification, and route optimization capabilities, reducing their effectiveness in modern urban environments. To address these challenges, the proposed IoT Smart Trash Bin Management System utilizes the ESP32 microcontroller to develop an intelligent and automated waste monitoring solution. The system integrates ultrasonic sensors to measure dry and wet waste levels, along with a wet/dry sensor for accurate waste segregation. An IR sensor enables touch-free lid operation using a servo motor, enhancing hygiene. Real-time status is displayed on an LCD, while a buzzer alerts when the bin reaches capacity. IoT connectivity allows continuous data transmission to cloud platforms for remote monitoring, and a GPS module provides location tracking for optimized waste collection routing. This smart system improves efficiency, reduces environmental impact, minimizes operational costs, and supports the development of sustainable and intelligent urban waste management systems.

Keywords: GPS Tracking, Internet of Things, Smart City Infrastructure, Smart Waste Management, Touch-Free Operation, Ultrasonic Sensor, Waste Level Monitoring, Waste Segregation

1. Introduction

The rapid growth of urban populations and increasing waste generation have created significant challenges in modern waste management systems [1]. It is estimated that global municipal solid waste will exceed 3.4 billion tons annually by 2050, driven by urbanization and changing consumption patterns [2]. Inefficient waste collection and management practices contribute to nearly 20–30% increase in operational costs, while also leading to environmental pollution and public health risks [3]. At the same time, smart waste management technologies are projected to grow at over 18% annually, reflecting the shift toward intelligent and sustainable urban infrastructure. In environments such as smart cities, residential complexes, industrial zones [4], and public spaces, there is a critical need for systems that provide real-time monitoring, efficient waste handling, and optimized resource utilization.

Traditional waste management systems rely on fixed collection schedules and manual inspection of waste bins [5]. These approaches often result in inefficient operations, where bins may overflow before collection or be emptied while still partially filled. Such inefficiencies lead to unnecessary fuel consumption [6], increased labor costs, and

poor hygiene conditions. Additionally, conventional systems do not support waste segregation at the source, making recycling and proper disposal more difficult [7]. The lack of real-time monitoring and communication further limits the ability of municipal authorities to manage waste effectively and respond promptly to changing conditions.

In real-time scenarios, these limitations create several critical challenges affecting urban cleanliness and sustainability. Overflowing bins can cause unhygienic conditions, foul odors, and the spread of diseases, especially in densely populated areas. Inefficient collection routes increase fuel usage and carbon emissions, contributing to environmental degradation [8]. The absence of automated segregation leads to improper waste disposal and reduced recycling efficiency. Furthermore, the lack of real-time alerts and location tracking prevents timely waste collection and route optimization [9]. These challenges highlight the need for an intelligent, IoT-based waste management system capable of real-time monitoring, automated segregation, and optimized collection strategies, ensuring improved efficiency, reduced costs, and a cleaner, more sustainable urban environment.

2. Literature Survey

Kaza et al. [10] proposed a global analysis of solid waste management trends and projections up to 2050, highlighting increasing waste generation and the need for sustainable management strategies. Bakhouch et al. [11] proposed a smart waste management system based on Internet of Things (IoT) technology that enabled real-time monitoring of waste bins using sensors and communication modules.

Talari et al. [12] proposed a review of smart cities based on IoT concepts, focusing on infrastructure, communication technologies, and urban service optimization. Duhayyim et al. [13] proposed a deep reinforcement learning-based waste object classification system for smart city recycling applications. The system enabled automated identification and sorting of waste materials.

Anagnostopoulos et al. [14] proposed IoT-enabled tip and swap waste management models for smart cities that optimized waste collection and exchange processes. Avancini et al. [15] proposed an IoT-based smart energy meter for smart grid applications that enabled real-time energy monitoring and management.

Bhattacharya [16] proposed the integration of blockchain and IoT technologies for supply chain management, enhancing transparency and traceability. Saha et al. [17] proposed an IoT-based smart waste management system addressing challenges during COVID-19 by enabling contactless monitoring and collection.

Ali et al. [18] proposed an IoT-based smart waste bin monitoring system for municipal solid waste management that enabled real-time tracking of bin status. Ramson et al. [19] proposed a wireless sensor network-based smart bin system that utilized distributed sensors for waste monitoring and management. Popa et al. [20] proposed a smart city platform for automated waste collection that integrated IoT devices and centralized control systems.

Rohit et al. [21] proposed a smart dual dustbin model for waste segregation using sensor-based detection to separate biodegradable and non-biodegradable waste. Vishnu et al. [22] proposed an IoT-enabled solid waste management framework for smart cities that integrated sensing, communication, and data analytics. Arthur et al. [23] proposed a survey of smart dustbin systems using IoT and deep learning, analyzing automated waste detection and classification techniques. Hussain et al. [24] proposed a comparative analysis of IoT-enabled waste management models using multi-agent simulation for smart cities. The system evaluated performance and efficiency across different models.

3. Proposed System

Figure 1 illustrates the architecture of a Smart Bin Management System built around the ESP32, designed for intelligent waste detection, classification, and management. The system is divided into two main sections: transmitting section and receiving section. The transmitting section consists of sensors such as ultrasonic sensors, IR sensor, and wet/dry sensor that detect waste level, presence, and type. The ESP32 processes this data and controls outputs including a servomotor for waste segregation, LCD for display, buzzer for alerts, and IoT for remote monitoring. Additionally, a GPS module is used for location tracking of waste bins or collection units. This system enables automated waste sorting, efficient monitoring, and smart collection management.

Step 1: RPS: The RPS provides stable voltage to the ESP32 and all connected sensors and modules, ensuring reliable operation.

Step 2: Waste Detection using Ultrasonic Sensors: Two ultrasonic sensors are used to measure the waste level inside the bin and detect the presence of objects. This helps determine when the bin is full or requires cleaning.

Step 3: Object Detection using IR Sensor: The IR sensor detects the presence of waste as it enters the bin, triggering the system to initiate classification and sorting processes.

Step 4: Waste Classification using Wet/Dry Sensor: The wet/dry sensor identifies whether the waste is biodegradable (wet) or non-biodegradable (dry). This classification is essential for proper waste segregation.

Step 5: Data Processing by ESP32: The ESP32 processes all sensor inputs and determines the type and condition of waste. Based on this analysis, it generates control signals for sorting and alert mechanisms.

Step 6: Waste Segregation using Servo Motor: The servomotor controls a mechanical flap that directs waste into appropriate compartments (wet or dry), enabling automatic waste segregation.

Step 7: LCD Display Output: The LCD displays real-time information such as bin status, waste level, and system notifications, allowing local monitoring.

Step 8: Buzzer Alert System: When the bin is full or abnormal conditions are detected, the buzzer is activated to alert users or maintenance personnel.

Step 9: IoT-Based Remote Monitoring: The ESP32 transmits data to a cloud platform via IoT, enabling authorities to monitor bin status, waste levels, and system performance remotely.

Step 10: GPS-Based Location Tracking: The GPS module provides real-time location data of the bin or waste collection unit, helping optimize waste collection routes and management.

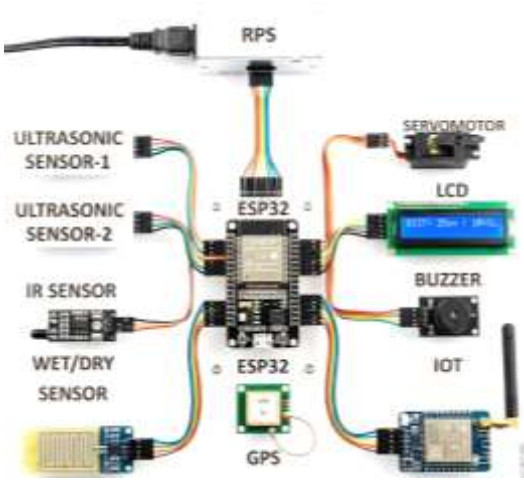

Figure 1. Proposed Block Diagram.

3.1 Working Procedure

The system as shown in Figure 2 detects incoming waste using sensors, classifies it as wet or dry, and automatically segregates it using a servo-controlled mechanism. It continuously monitors bin levels and sends alerts when full. All data is displayed locally and transmitted to the cloud for remote monitoring, while GPS enables location tracking for efficient waste collection. This integrated approach enhances waste

management efficiency, reduces manual effort, and supports smart city initiatives.

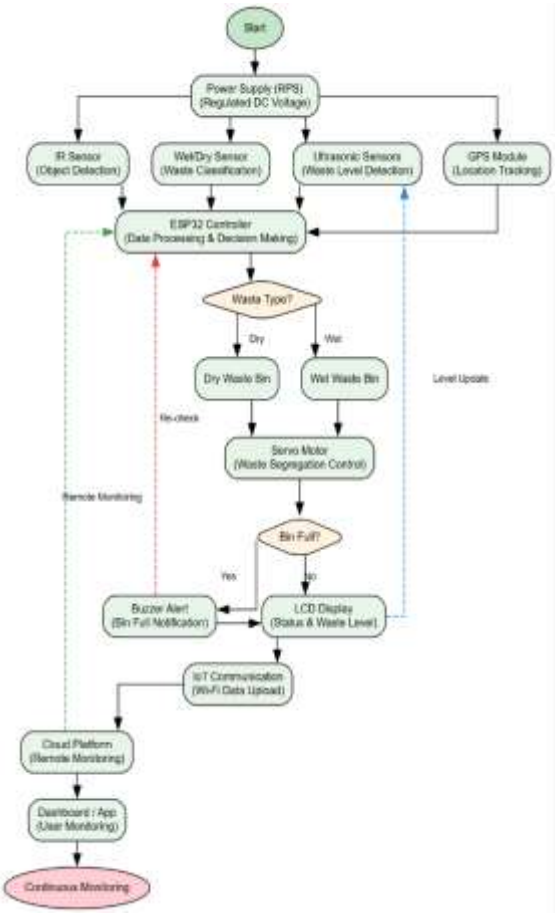

Figure 2. Proposed Flowchart.

Figure 3 illustrates the circuit diagram of an ESP32-based IoT smart waste management system designed for automated waste monitoring and segregation. The system is powered by a regulated power supply unit consisting of a step-down transformer, bridge rectifier, filter capacitors, and a 7805-voltage regulator to provide a stable +5V supply. The ESP32 microcontroller acts as the central control unit, interfacing with ultrasonic sensors to measure the fill level of waste bins and detect proximity. A GPS module enables location tracking of waste bins, while an IR sensor is used for waste detection and classification. A servo motor mechanism is integrated for automatic lid control or waste segregation. The system includes an IoT module for real-time data transmission and remote monitoring, and a 16×2 LCD to display bin status and system information. Additionally, a buzzer provides alert notifications when the bin reaches maximum capacity. This intelligent system improves waste collection efficiency, reduces overflow issues, and supports smart city waste management solutions.

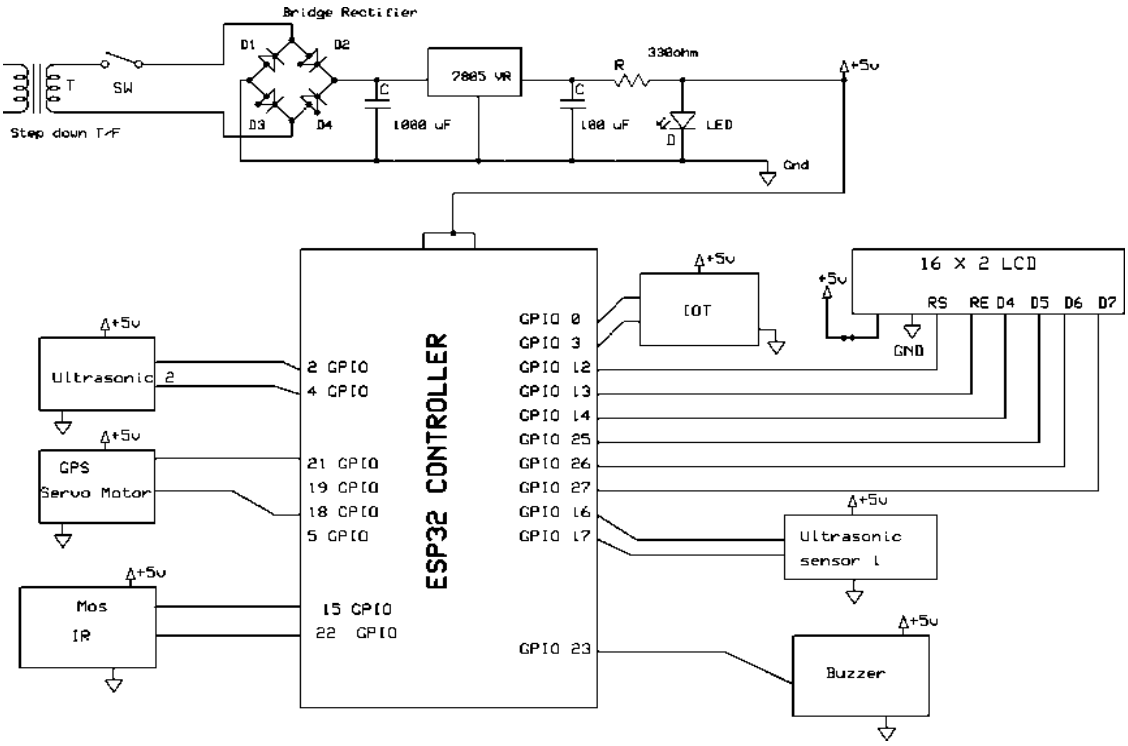

Figure 3. Circuit Diagram of ESP32-Based IoT Smart Waste Management System.

4. Results and Discussion

Figure 4 shows the transmitting section of smart bin project, featuring sensor-based waste segregation with an ESP32 controller, ultrasonic and IR sensors, an LCD display, and GPS for IoT-based monitoring.

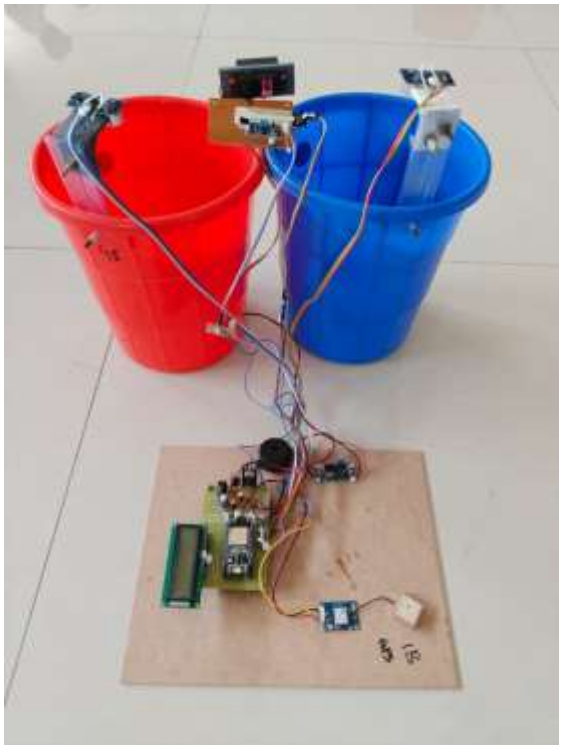

Figure 4. Smart bin hardware setup

Figure 5. Outputs with LCD Initialization.

Figure 5 displays the control circuit of the IoT Smart Bin Management system, featuring an ESP32 microcontroller, LCD display, power regulation module, and connected sensors for waste monitoring and segregation.

5. Conclusion

The proposed IoT smart trash bin management system provides an efficient and intelligent solution to modern waste management challenges by integrating real-time monitoring, automation, and IoT connectivity. By utilizing the ESP32 microcontroller along with ultrasonic sensors, wet/dry detection, and IR-based touch-free operation, the system ensures accurate waste level measurement, hygienic usage, and effective segregation. The inclusion of GPS tracking enables optimized waste collection routes, reducing fuel consumption and operational costs, while LCD display and buzzer alerts provide immediate local feedback. IoT integration allows continuous remote monitoring and data analysis, supporting better decision-making and timely waste collection. This system overcomes the limitations of traditional methods by preventing overflow, improving sanitation, and enhancing overall efficiency.

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